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Bio-inspired optimization algorithms applied to rectenna design

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Abstract
A comparative study of the use of bio-inspired optimization technologies including the Cuckoo Search (CS) algorithm, the Differential Evolution (DE) algorithm, and Quantum-behaved Particle Swarm Optimization (QPSO) in the design of microstrip patch antennas for use in RF energy harvesting systems is presented. Radio frequency (RF) energy harvesting is considered as an eco-friendly energy source and has become a focus of intense research especially for use in distributed sensor networks. In a RF energy harvesting system, the antenna is responsible for capturing RF signals over a certain frequency band, and it is a vital element in determining the performance of the RF energy harvester. In this paper, a new mathematical weighted evaluation model involving antenna efficiency, center frequency, and bandwidth is proposed to evaluate the performance of a rectangular microstrip patch antenna (RMPA) for a RF harvesting system based on both the transmission-line model and the cavity model. With the evaluation model as the objective function, bio-inspired optimization approaches are utilized to determine the geometrical parameters of the optimal antenna based on given constraints. Moreover, the optimised designs of an antenna for harvesting energy from the Global System for Mobile Communications (GSM) frequency band are proposed via the mathematical model and bio-inspired optimization approaches using simulations. Furthermore, a comparative study of the DE, CS, and QPSO techniques is conducted via the evaluation of the properties of the antenna designs.

Keywords: RF harvesting system, Microstrip antenna, Cuckoo Search (CS) algorithm, Differential Evolution (DE) algorithm, Quantum-behaved particle swarm optimization (QPSO)

Background

With the advance of technologies including the Internet of Things (IoT) and wearable electronics, the demand for mobile electrical devices has surged. Battery depletion has become a fundamental bottleneck which limits the performance of these devices [1]. Considering the conventional fact that batteries have to be replaced or replenished manually after depletion, deeper implications exist for devices such as implantable heart pumps for which the replacement or recharging of the battery by cable is inconvenient and high-cost [2]. RF energy harvesting technology provides an alternative to this and has recently received significant attention in the research community demonstrating its potential as a sustainable energy source for low power electronics [3–7].

The general anatomy of an RF energy harvester has been explained and examined. Some state of the art designs for receiving antenna including both narrow-band and broad band antennas have been introduced. A mathematical weighted evaluation model involving antenna efficiency, center frequency, bandwidth, and gain was proposed to evaluate the performance of a RMPA for a RF harvesting system.The heuristic optimization approaches CS, DE, and QPSO were introduced and then utilized to give optimal designs for a GSM1800 receiving antenna. The proposed optimization algorithms successfully achieved optimal solutions under two different antenna size constraints. The overall comparison between QPSO, DE, and CS showed that the DE based optimization design approach provides the best solution and hence has the best globally optimum value search ability. This can significantly enhance antenna performance. Moreover, among the three optimization approaches, the CS algorithm has the best robustness. Furthermore, the simulations using QPSO based algorithm indicate its superiority displaying a faster convergence speed than DE and CS in the application of solving a complex electromagnetic problem. The advance of wireless communication has been boosting the power density of ambient RF energy. Among various sources of available ambient RF energy, the GSM frequency bands, including GSM1800 and GSM900, the Industrial, Scientific and Medical (ISM) band and the 3G band are the most promising to be explored. The average power densities of the conventionally utilized frequency bands measured in 2012 at all underground stations in London are summarized in Table 1 [8].

In brief, the RF energy harvester has the capability to convert RF signals (AC signal in nature) from ambient RF energy sources into a DC source. A typical centralized architecture of a RF energy harvesting system is shown in Fig. 1, it has two main components: a power management component and a rectenna. The rectenna consists of a receiving antenna, a matching circuit and a rectifier [4, 6]. The power management module has two approaches for controlling the incoming energy flow: harvest-use and harvest-store-use. The receiving antenna is responsible for capturing RF signals in the design frequency band, and it is a vital element in determining the performance of the energy harvesting system. Microstrip antennas have been greatly utilised in many communication technologies due to their low profile structure and low manufacturing cost [9]. In this study, the rectangular microstrip patch antenna (RMPA) is chosen for the rectenna design. The design will be optimized using 3 bio-inspired optimisation techniques The optimisation of a microstrip antenna for a RF energy harvester can be interpreted as a multi-objects nonlinear optimization problem. The solutions for an optimal patch antenna design can be attained by heuristic optimization algorithms.

Recently, considerable research has been directed towards the enhancement of antenna performance in RF harvesting systems. A variety of types of antenna design have been investigated including: fractal antennas, microstrip antennas and monopole antennas

Table 1 Average RF power density in London [8]

Band name	Frequency band	Average power density
GSM1800 (BTx)	1805 MHz ∼ 1880 MHz	84 nW/cm^2
GSM1800 (MTx)	1710 MHz ∼ 1785 MHz	0.5nW/cm^2
GSM900(BTx)	925 MHz∼ 960MHz	36nW/cm^2
GSM900(MTx)	880 MHz∼ 915MHz	0.45 nW/cm^2
3G (BTx)	2110 MHz ∼ 2170 MHz	12 nW/cm^2
3G (MTx)	1920 MHz ∼ 1980 MHz	0.46 nW/cm^2
WiFi	2400 MHz ∼ 2500 MHz	6 nW/cm^2

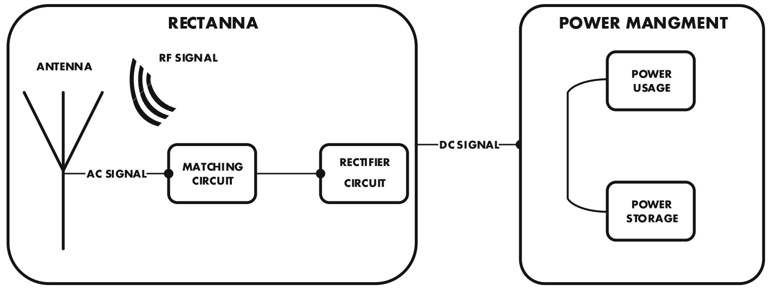

Fig. 1 Architecture of RF harvesting system. This figure shows a typical centralized architecture of a RF energy harvesting system, including two main components: a power management component and a rectenna

[10–12]. Table 2 shows the antenna performance of some state of art designs. As shown in Table 2, research efforts have been made for broad-band antenna(typical on order of 1GHz) as in [13–17, 42], and for narrow-band antenna in [10, 39–41, 43]. The dipole antenna is the focus of the work in [13, 16], and the monopole in [11, 41]. Authors in [17, 39, 40, 43] have demonstrated the excellent performance of the microstrip antenna. Nevertheless, most of the designs that have been mentioned previously do not consider the minimization of antenna size, which could potentially limit the application of the RF harvester. In [18–23], heuristic optimization approaches including the DE and CS algorithms have been utilized to determine the geometrical characteristics of the optimal patch antenna. Conventionally, patch antennas suffer from a narrow bandwidth. Accordingly, PSO and curve fitting have been introduced in [18], and the overall bandwidth of the inverted E-shaped microstrip patch antenna was increased by 15%. Authors in [20–23] have proposed mathematical models of the RMPA considering the center frequency as well as return loss, and the optimal designs are obtained via the CS, PSO, and DE algorithms. However, none of them involve improving antenna gain, widening antenna bandwidth, and minimization of antenna size.

Method

In a RF energy harvesting system, the antenna, which is responsible for receiving RF signals over a certain frequency band, is an important element in the design of the RF energy harvester. The design of the antenna involves several parameters, some of which induce

Table 2 Summary of performance of variety of up-to-date antenna design

Literature	Antenna type	Designed band	Antenna gain	Return loss
M. Arrawatia, et al. [39]	Differential Microstrip	0.87 GHz ∼ 1.05 GHz	8.5 dBi	17.2984 dB
S. Ghosh, et al. [40]	Microstrip	0.935 GHz ∼ 0.96 GHz	4.0947 dB	12.82 dB
H. Saghlatoon, et al. [41]	Planar Monopole	0.6 GHz ∼ 1.5 GHz	3.432 dBi	27.5 dB
A. Dadgarpour, et al. [42]	Bow-tie	2.5 GHz ∼ 3.9 GHz	≥ 10.9 dBi	27.68 dB
M. W. Zeng, et al. [10]	Fractal Loop	1.73 GHz ∼ 1.84 GHz	3.2 dBi	31.25 dB
M. Arrawatia, et al.[11]	Triangular Monopole	0.85 GHz ∼ 1.94 GHz	≥ 2 dBi	19.085
J. Wen, et al.[13]	Dipole	1.7 GHz ∼ 3.6 GHz	9.05 dBi	33.75 dB
D. Yang, et al.[14]	Planar Quasi-Yagi	3.15 GHz ∼ 10.65 GHz	7.6 dBi	24.714 dB
R. Maher, et al. [15]	Planar	2.1 GHz ∼ 7GHz	11.4585 dBi	44.1499
J. Y. Li, et al. [16]	Dipole	2.48 GHz ∼ 9.51GHz	≥ 6dBi	19.08
K. P. Esselle, et al. [17]	Microstrip	4 GHz ∼ 9.5GHz	≥ 7.4 dBi	35
W. Han, et al. [43]	Circular Microstrip	6.12 GHz ∼ 6.84 GHz	8.7 dBi	14 dB

contradictory modifications of antenna performances. In this paper, a new mathematical weighted evaluation model involving antenna efficiency, center frequency, and bandwidth is proposed to evaluate the performance of a rectangular microstrip patch antenna (RMPA) based on both the transmission-line model and the cavity model. With the mathematic modeling of a RMPA, three bio-inspired optimization technologies including the Cuckoo Search (CS) algorithm, the Differential Evolution (DE) algorithm, and Quantum-behaved Particle Swarm Optimization (QPSO)are used to optimize the design of RMPA with certain constraints. The simulation processes and designed antennas' performances are also presented and compared. With the evaluation model as the objective function, bio-inspired optimization approaches are utilized to determine the geometrical parameters of the optimal antenna based on given constraints.

The paper is organized as follows:"Mathematic modeling of RMPA"section introduces the basic architecture and properties of a RMPA, and a mathematical model is proposed based on the cavity and transmission line models. Additionally, the objective function and constraints for optimization are derived. The"Bio-inspired algorithms for antenna design" section describes the current implementation of the optimal antenna design algorithms including QPSO, CS, and DE. Finally, based on the performance of designed antennas, the properties of three bio-inspired algorithms are discussed and compared.

Mathematic modeling of RMPA

The efficiency of a RF energy harvester is defined as the ratio of output power (P_{out}) over input power (P_{in}). Conventionally, the harvested RF power from the rectenna is expressed as follows:

$$P_{out} = \eta_a \cdot \eta_m \cdot \eta_r \cdot P_{in} \tag{1}$$

where the η_a, η_m and η_r respectively represent the efficiency of receiving antenna, impedance matching network, and rectifying circuit. The magnitude of P_T is correlated with the design frequency band of antenna. Accordingly, the optimum antenna design for a RF harvesting system requires two features: high antenna efficiency and appropriate frequency band. In more detail, the performance of the antenna used for a RF energy harvester mainly depends on the antenna gain, bandwidth, return loss, and center frequency. However, there is a trade-off between antenna size and performance.

Architecture of a RMPA

The typical architecture of a rectangular microstrip patch antenna (RMPA) with inset feed contains four geometric parameters (L, W, g, L_d) as shown in Fig. 2, and it consists of three layers including patch, substrate, and ground plane. Normally the patch and microstrip feed line are fabricated on the upper surface of the dielectric substrate, and a metal ground plane is placed on the bottom. The four most popular feeding configurations are: the microstrip line, coaxial probe, aperture coupling, and proximity coupling, among which the inset microstrip feed line has the simplest configuration to implement and control [9] By far, the rectangular patch is the most widely used microstrip antenna, and can be modeled and analyzed by both transmission line model and cavity theory. The mathematical formulations of the RMPA have been demonstrated and derived in the following section, where the notations used in the model are as shown in Tables 3 and 4.

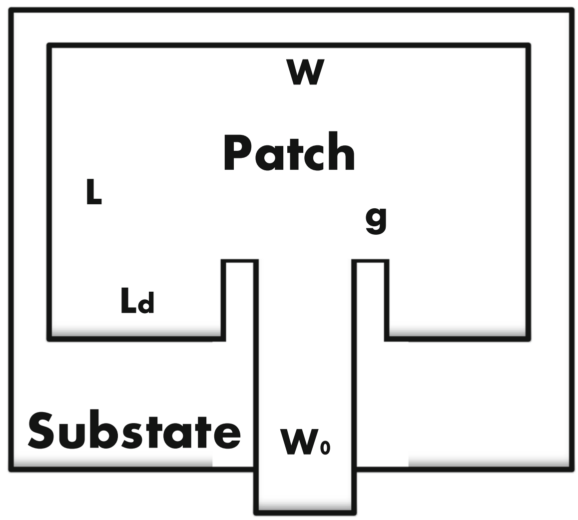

Fig. 2 Architecture of a RMPA. This figure shows the typical architecture of a three-layer rectangular microstrip patch antenna (RMPA) with inset feed contains four geometric parameters (L, W, g, Ld)

Problem formulation

The objective function is to minimize the deviation between the designed antenna and the optimum antenna.

$$\begin{cases} \Phi(W, L, y_0, g, W_0) = [\delta B, \delta A_e, \delta G] \cdot W^{\mathbf{T}} \\ Obj.Fun = \min \Phi(W, L, y_0, g) \end{cases} \quad (2)$$

Table 3 Nomenclature of important parameters

F	Center frequency of antenna	A_e	Antenna efficiency of antenna
B	Band width of antenna	R_L	Return loss of antenna
P_{in}	Input power of rectenna	P_{out}	Output power of rectenna
η_a	Efficiency of antenna	η_m	Efficiency of matching circuit
η_r	Efficiency of rectifier circuit	P_T	Transmitted power from source
W	Width of RMPA	L	Length of RMPA
W_0	Feed width of RMPA	L_d	Inset feed length
g	Notch width	ε_0	Vacuum dielectric constant
X_{min}	Minimum constraint of antenna size	X_{max}	Maximum constraint of antenna size
μ_0	Vacuum permeability	Z_{in}	Antenna input impedance
Γ	Voltage reflection coefficient	VSWR	Voltage standing wave ratio
Q_{rad}	Quality factor due to radiation losses	Q_c	Quality factor due to conduction losses
Q_d	Quality factor due to dielectric losses	Q_{sw}	Quality factor due to surface waves
Q_t	Total quality factor	$\tan\delta$	Loss tangent of the substrate material
G	Antenna gain	v_0	The speed of EM wave
k_0	Spatial angular frequency of wave	G_{abs}	Absolute gain
P_{rad}	Radiation power of antenna	U_{max}	Maximum radiation intensity
D_0	Directivity of antenna with single slot	D_{AF}	Directivity of array factor AF
e_{BW}	Efficient bandwidth ratio	F_{AL}	Aimed lower conner frequency
F_{AH}	Aimed upper conner frequency	F_{DL}	Designed lower conner frequency
F_{DH}	Designed upper conner frequency	σ	Conductivity of patch
D	Directivity of antenna	e_{cd}	ntenna Radiation efficiency

Table 4 Nomenclature of important parameters

$\hbar$	Planck's constant
$V(r)$	Potential energy distribution
Mbest	Best position of particle in the direction d
β	Contraction-expansion coefficient
$p_{j,d}$	Local attractor of particle j in direction d
u	Gaussian distributed number within [0,1]
k	Random value within [0,1]

where W = $[w_1\ w_2\ w_3]$ is a weight matrix. Moreover, δF, δB, δA_e, and δR_L shows the deviation between the performance of designed antenna and the performance of the optimal antenna. The inequality geometry constraints are five groups of inequations which can be obtained from the architecture of RMPA

$$\begin{cases} g < \frac{L}{2} \\ y_0 < L \\ X_{min} < L < X_{max} \\ X_{min} < W < X_{max} \end{cases} \tag{3}$$

Moreover, the geometrical requirement for applying the transmission line model of the RMPA is [9].

$$W \gg h. \tag{4}$$

Input impedance of a RMPA

The input impedance of the RMPA Z_{in} can be obtained from the equivalent transmission line circuit as shown in Fig. 3. The admittance of the antenna with two slots (Y_1 and Y_2) is given by [24–26]:

$$Y_1 = G_1 + jB_1 \tag{5}$$

$$Y_2 = G_2 + jB_2 \tag{6}$$

where G_1 = G_2, B_1 = B_2 and owing to that the two slots of the antenna are identical.

With the field expression derived according to the cavity model [9, 25], the conductance of a single slot is defied as follows:

$$G_1 = \frac{2P_{rad}}{|V_0|^2}. \tag{7}$$

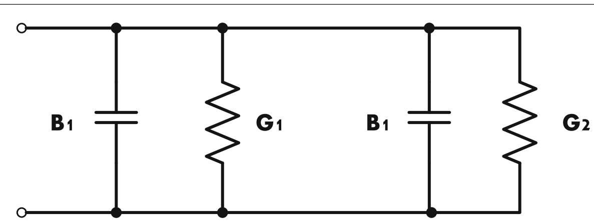

Fig. 3 Equivalent transmission line model circuit. This figure shows the equivalent transmission line model circuit of a RMPA, including capacitances and resistances

where P_{rad} is defined as the radiated power which can be calculated by [25, 26]:

$$P_{rad} = \frac{|V_0|^2}{2\pi\eta_0}\int_0^{\pi}\left[\frac{\sin\left(\frac{k_0W}{2}\cos\vartheta\right)}{\cos(\vartheta)}\right]^2 \sin^3\vartheta\,\delta\vartheta. \tag{8}$$

Accordingly, the conductance of the antenna is defined as:

$$G_1 = G_2 = \frac{1}{120\pi^2}\int_0^{\pi}\left[\frac{\sin\left(\frac{k_0W}{2}.\cos\vartheta\right)}{\cos(\vartheta)}\right]^2 \sin^3\vartheta\,\delta\vartheta. \tag{9}$$

Considering the mutual effect between the two slots, the total resonant input admittance of the RMPA with no inset feed can be obtained as [9, 24]:

$$\begin{cases} \dot{Y}_2 = G_1 - jB_1 \\ Y = Y_1 + \dot{Y}_2 = 2(G_1 + G_{12}) \end{cases} \tag{10}$$

where the mutual conductance G_{12} is [9, 24, 26].

$$G_{12} = \frac{1}{120\pi^2}\int_0^{\pi}\left[\frac{\sin\left(\frac{k_0W}{2}\cos\vartheta\right)}{\cos(\vartheta)}\right]^2 J_0\left(k_0L\sin\vartheta\right) sin^3(\vartheta)\delta\vartheta \tag{11}$$

where J_0 is the Bessel function of the first kind of order zero, and accordingly the input resistance for the inset feed case can be approximately expressed as [26]:

$$Z_{in} = \frac{1}{2\left(G_1 + G_{12}\right)}\cos^2\left(\frac{\pi}{L}L_d\right). \tag{12}$$

Resonant frequency of A RMPA

Owing to the fact that the dimensions of patch are not infinite along the length and width, the fields at the edges of patch is nonhomogeneous. Figure 4 shows typical electric field lines caused by the fringing effect, which makes the electric size of the patch larger than the physical dimensions. Thus, the effective dielectric constant ϵ_{eff} and effective patch width L_{eff} are introduced to take account of the fringing effect. Accordingly, the resonant frequency of the dominant mode of the RMPA is derived as [9, 24, 25].

$$F\left(W, L, y_0, g\right) = \frac{1}{2L_{eff}\sqrt{\varepsilon_{reff}}\sqrt{\mu_0\varepsilon_0}} \tag{13}$$

The effective dielectric constant ϵ_{eff} and effective patch length L_{eff} can be calculated by:

$$\begin{cases} \varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1 + 12\frac{h}{W}\right]^{-1/2} \\ L_{eff} = L + 2\Delta L \end{cases} \tag{14}$$

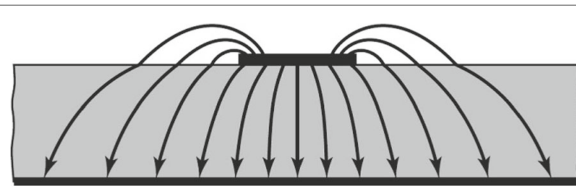

Fig. 4 Electric field caused by fringing effect. This figure shows the typical electric field lines of a RMPA

where ΔL is the normalized extension of the length and given as:

$$\Delta L = 0.412h \frac{\left(\varepsilon_{reff} + 0.3\right)\left[\frac{W}{h} + 0.264\right]}{\left(\varepsilon_{reff} - 0.258\right)\left[\frac{W}{h} + 0.8\right]}. \tag{15}$$

The notch width can be calculated based on the designed center frequency, and the empirical equation for which is proposed as [27]:

$$g = \frac{v_0}{\sqrt{2\epsilon_{eff}}} \frac{4.65 \cdot 10^{-12}}{f} \tag{16}$$

Antenna gain of a RMPA

Antenna gain is defined as the ratio of radiation intensity in a given direction to the intensity that would be obtained when the power accepted is isotropically distributed [9]. The relative gain is the ratio of power gain to the gain of a reference antenna [9]. Antenna gain is mathematically deified as [9, 24]:

$$G(W, L, y_0, g) = 4\pi \frac{U(\theta, \phi)}{P_{in}} \tag{17}$$

Antenna gain can also be expressed as a function of antenna directivity as:

$$G(\theta, \phi) = e_{cd}[\,4\pi U(\theta, \phi)] = e_{cd} D_t \tag{18}$$

Hence, antenna gain depends on radiation efficiency as well as directivity. The two parameters are calculated separately as follows.

The quality factor of the antenna, or the figure-of-merit, is representative of antenna loss, and it in general can be written as [9, 26]:

$$\frac{1}{Q_t} = \frac{1}{Q_{rad}} + \frac{1}{Q_c} + \frac{1}{Q_d} + \frac{1}{Q_{sw}} \tag{19}$$

where the quality factors of various losses can be expressed as :

$$\begin{cases} Q_c = h\sqrt{\pi f \mu \sigma} \\ Q_d = \frac{1}{\tan(\delta)} \\ Q_{rad} = \frac{2\omega \epsilon_r K}{h G_t / l} \end{cases} \tag{20}$$

As for the RMPA aperture operating in the dominant TM^x_{010} mode, the G_t/l and K can be calculated by [9].

$$\begin{cases} K = \frac{\iint_{area} |E|^2 dA}{\oint_{perimeter} |E|^2 dl} = \frac{L}{4} \\ G_t/l = \frac{G_1}{W} \end{cases} \tag{21}$$

In an ideal situation the loss caused by conduction Q_c and the loss by surface wave Q_{sw} can be ignored. Thus, the total loss can be approximately expressed as:

$$Q_t = \frac{Q_d Q_{rad}}{Q_d + Q_{rad}} \tag{22}$$

and e_{cd}, the radiation efficiency of an antenna, can be derived through the quality factor as:

$$e_{cd} = \frac{Q_t}{Q_{rad}} = \frac{Q_d}{Q_d + Q_{rad}} \tag{23}$$

Furthermore, directivity, one of the most important antenna parameters, conventionally implies the ratio of maximum radiation intensity to the averaged value over all directions, and is expressed by:

$$D_t = \frac{4\pi U_{max}}{P_{rad}} \tag{24}$$

In the case of a RMPA with two radiating slots, the antenna directivity can be calculated by following equation [24, 25].

$$D_t = D_0 D_{AF} \tag{25}$$

where the directivity for an antenna with one slot D_0 is defined as [24]:

$$D_0 = \left(\frac{4\pi^2 W^2}{\lambda_0^2}\right) / \left(\int_0^{\pi} \left[\frac{\sin\left(\frac{k_0 W}{2}\cos\vartheta\right)}{\cos(\vartheta)}\right]^2 J_0\left(k_0 L \sin\vartheta\right) sin^3(\vartheta)\delta\vartheta\right). \tag{26}$$

Moreover, the directivity of the array factor AF D_{AF} is calculated as follows [9]:

$$D_{AF} = \frac{2}{1 + G_{12}/G_1} \tag{27}$$

Therefore, the antenna gain in dBi can be demonstrated by the following equation.

$$D_t = \left(\frac{8\pi^2 W^2}{\lambda_0^2}\right) / \left(\left(\int_0^{\pi} \left[\frac{\sin\left(\frac{k_0 W}{2}\cos\vartheta\right)}{\cos(\vartheta)}\right]^2 J_0\left(k_0 L \sin\vartheta\right) sin^3(\vartheta)\delta\vartheta\right) \cdot (1+G_{12}/G_1)\right) \tag{28}$$

Thus, the antenna gain can be obtained via the directivity and radiation efficiency of RMPA as shown in Eq. 29.

$$G\left(W, L, y_0, g\right) = \frac{Q_d}{Q_d + Q_{rad}} D_t \tag{29}$$

Deviation between the designed antenna gain and the optimal antenna gain (here we use 10 dBi as the desired gain) is defined as follows.

$$\delta G\left(W, L, y_0, g\right) = \left(10 - \frac{Q_d}{Q_d + Q_{rad}} D_t\right) / 10 \tag{30}$$

Antenna efficiency of a RMPA

The overall antenna efficiency due to mismatch reflections and IR^2 losses is used to consider losses at the input terminals and within the antenna. Thus, the antenna efficiency can be written as:

$$A_e = e_r e_{cd} = e_{cd}\left(1 - |\Gamma|^2\right) \tag{31}$$

In the transmission line model circuit, the return loss is determined by both the VSWR and Γ which can be calculated using:

$$\begin{cases} \Gamma = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \\ VSWR = \frac{1+|\Gamma|}{1-|\Gamma|} \end{cases} \tag{32}$$

In telecommunications systems, return loss is defined as the power loss for the signal reflected by a discontinuity during transmission, and it is mathematically defined as:

$$R_L\left(W, L, y_0, g\right)_{dB} = 10\log_{10} P_i / P_0 \tag{33}$$

Assuming the characteristic impedance of the feed line is equal to 50 Ω, the return loss can be expressed by Eq. (34), The input independence of the RMPA has also been calculated using Eq. (12).

$$\begin{cases} R_L\left(W, L, y_0, g\right)_{dB} = -20\log_{10}\left(|\Gamma|\right) = -20\log_{10}\frac{Z_{in}-50}{Z_{in}+50} \\ R_L\left(W, L, y_0, g\right)_{dB} = -20\log_{10}\left(\frac{cos^2\left(\frac{\pi}{L}d\right)-100(G_1+G_{12})}{cos^2\left(\frac{\pi}{L}d\right)+100(G_1+G_{12})}\right) \end{cases} \quad (34)$$

Therefore, the overall antenna efficiency can be expressed as follows:

$$A_e\left(W, L, y_0, g\right) = e_r e_{cd} = \frac{Q_d}{Q_d + Q_{rad}}\left(1 - \left(\frac{cos^2\left(\frac{\pi}{L}d\right) - 100\left(G_1 + G_{12}\right)}{cos^2\left(\frac{\pi}{L}d\right) + 100\left(G_1 + G_{12}\right)}\right)^2\right) \quad (35)$$

Additionally, the derivation between designed antenna efficiency and the optimal antenna efficiency can be defined as:

$$\delta A_e\left(W, L, y_0, g\right) = |(1 - A_e)| \quad (36)$$

Bandwidth of a RMPA

The magnitude of the bandwidth varies with VSWR. The bandwidth and percentage bandwidth of an antenna (VSWR ≤ 2) can be calculated by:

$$\begin{cases} \%BW\left(W, L, y_0, g\right) = \frac{Ah}{\lambda_0\sqrt{\epsilon_r}}\sqrt{\frac{W}{L}} \\ BW\left(W, L, y_0, g\right) = \frac{Ah}{\lambda_0\sqrt{\epsilon_r}}\sqrt{\frac{W}{L}} \cdot F\left(W, L, W_0, y_0, g\right) \end{cases} \quad (37)$$

where A can take one of the three following values [28]

$$A = \begin{cases} 180, \ \frac{Ah}{\lambda_0\sqrt{\epsilon_r}} \leq 0.045 \\ 200, \ 0.045 \leq \frac{Ah}{\lambda_0\sqrt{\epsilon_r}} \leq 0.075 \\ 220, \ 0.075 \leq \frac{Ah}{\lambda_0\sqrt{\epsilon_r}} \end{cases} \quad (38)$$

Moreover, the percentage bandwidth can also be calculated using the quality factor and the corresponding VSWR, as [9].

$$\frac{\delta f}{f_0} = \frac{VSWR - 1}{Q_t\sqrt{VSWR}} \quad (39)$$

To demonstrate the accuracy of the design frequency band, concept of efficient covered bandwidth ratio is proposed as below. Figure 5 shows the physical meaning of efficient covered bandwidth which describes the region of the desired frequency bandwidth

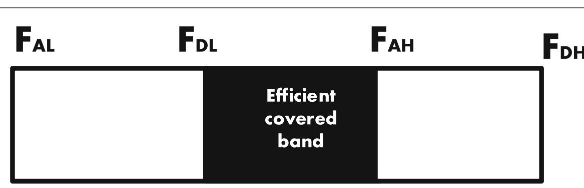

Fig. 5 Defined efficient bandwidth. This figure shows the physical meaning of efficient covered bandwidth which describes the region of the desired frequency bandwidth covered by the design bandwidth

covered by the design bandwidth. Thus, the efficient covered bandwidth ratio e_{BW} is proposed mathematically as:

$$e_{BW} = \begin{cases} \frac{f_{DH}-f_{DL}}{f_{AH}-f_{AL}}, & F_{DH} \leq F_{AH}, F_{AL} \leq F_{DL} \\ \frac{f_{DH}-f_{AL}}{f_{AH}-f_{AL}}, & F_{DH} < F_{AH}, F_{DL} < F_{AL} \\ \frac{f_{AH}-f_{DL}}{f_{AH}-f_{AL}}, & F_{AH} < F_{DH}, F_{AL} < F_{DL} \\ 0, & F_{DH} \leq F_{AL} \quad \text{or} \quad F_{AH} \leq F_{DL} \end{cases} \tag{40}$$

Thus, the derivation between design antenna bandwidth and the optimal antenna bandwidth (VSWR ≤ 2) is described by Eq. (41):

$$\delta B_e(W, L, y_0, g) = e_{BW} \tag{41}$$

Bio-inspired algorithms for antenna design

CS algorithm for antenna design

The Cuckoo Search (CS) algorithm is a stochastic global search algorithm, inspired by obligated brood parasitic behavior of some cuckoo species, and it was developed by Xin-She Yang and Deb in 2009 [29, 30]. The cuckoo search imitates aggressive reproduction strategy of some species of cuckoo birds in nature. The process of CS follows three idealized rules [29]: 1) Each cuckoo lays one egg in a random nest which will be a potential solution. 2) The next generation of eggs will only be carried over by the best nests with the highest quality of eggs, which proposes only locally optimal solutions can survive in next generation. 3) The number of available host nests is fixed, and eggs laid by the cuckoo can be discovered by the host birds with a probability equal to P_a. The general system-equation of the CS is based on lévy flight as [29]:

$$x^{t+1} = x^t + \alpha \oplus lévy(\lambda) \tag{42}$$

where x^t is the current solution, and x^{t+1} is the newly generated solution. Additionally, the $lévy(\lambda)$ follows the *lévy* distribution [29].

$$lévy(\lambda) \sim t^{-\lambda} \quad (1 \leq \lambda \leq 3). \tag{43}$$

The step size α follows the Mantegna Algorithm in which the step size can be obtained by [29, 30]:

$$\alpha = \frac{u}{|v|^{1/\beta}} \tag{44}$$

where the u as well as v follow normal distribution [29].

$$\begin{cases} \sigma u = \frac{\Gamma(1+\beta)\sin\pi(\beta/2)}{\Gamma(1+\beta)/(2\beta)2^{(\beta-1)/2}} \\ \sigma v = 1 \end{cases} \tag{45}$$

When the β is set to 1, the above two formula reduce to Eq. (46).

$$\begin{cases} \sigma u = \frac{\Gamma 2}{\Gamma 1} = 1 \\ \sigma v = 1 \end{cases} \tag{46}$$

Therefore, the overall procedure of optimizing the antenna design for a RF harvesting system is shown as Algorithm 1, which has been implemented by MATLAB and Python.

Differential evolution for RMPA design

Differential evolution (DE), one of the most powerful stochastic and population based optimization algorithms, is inspired by the Darwinian principles for the natural evolution

Algorithm 1: CUCKOO SEARCH FOR OPTIMAL ANTENNA DESIGN IN RF ENERGY HARVESTER

Input : Antenna size constraint, Objective frequency band
Output: Geometric architecture of optimal antenna, Performance of designed antenna
Objective Function: $\Phi(W, L, y_0, g)$;
Initialization of n host nests x_i (i = 1,2,...,n) ;
while $t \leq$ *Maximum Generation* **do**
  $x^{i+1} = x^i + \alpha \oplus l\acute{e}vy(\lambda)$;
  Evaluate the fitness value Φ_i ;
  Choose a nest among n (called nest j) randomly;
  if $F_j \leq F_i$ **then**
    Replace j by the new solution
  else
    Local optimum value does not change
  end
  A fraction (P_a) of worse nests were abandoned and repalced by new nests ;
  if $rand \leq P_a$ **then**
    Replace the nests by random walk
  else
    The solution would remain
  end
  Solutions are ranked and the locally optimal value is found ;
  if *Out of bounder* **then**
    Generation of new solution: $x_i^j = x_{min}^j + randn(0,1) \cdot \left(x_{max}^j - x_{min}^j\right)$
  else
    Continue
  end
  Solutions are ranked and the locally optimal value is found ;
end
Search the global optimum design of RMPA antenna ;
End

of species. DE was initially introduced by Storn and Price in 1996 [31–33]. As a variant of the Genetic Algorithm (GA), DE mainly has three advantages including easy implementation, high performance and few control parameters [32, 33]. The overall procedure for DE has four steps: initialization, mutation, crossover and selection. Firstly, the initial value of the *j*th parameter in the *i*th individual at generation zero is given by [33].

$$x_i^j = x_{min}^j + randn(0,1) \cdot \left(x_{max}^j - x_{min}^j\right) \tag{47}$$

where the randn (0,1) is a uniformly distributed random variable. The mutation operation will be employed to generate a new potential solution, of which there are five frequently used mutation strategies [33]. The equation for the DE/rand/1 strategy is given by [33].

$$V_{i,G} = X_{r_1,G} + F \cdot (X_{r_3,G} - X_{r_2,G}) \tag{48}$$

where $V_{i,G}$ are the mutant solutions generated by the current solutions including $X_{r_1^i,G}$, $X_{r_2,G}$, and $X_{r_3,G}$. Here F is a positive control factor. After the mutation, the crossover operation is applied to generate more potential new solutions based on $V_{i,G}$ and $X_{i,G}$ [32]:

$$U_{i,G}^{j} = \begin{cases} V_{i,G}^{j} \text{if} rand_j[0,1] \leq CR \\ X_{i,G}^{j} \text{if} rand_j[0,1] > CR \end{cases} \tag{49}$$

Finally, the locally optimal solutions will be selected and the global optimum value can be found. Based on the four steps mentioned, the overall pseudo code also implemented in MATLAB and Python is shown as Algorithm 2.

Algorithm 2: DIFFERENTIAL EVOLUTION FOR OPTIMAL ANTENNA IN RF ENERGY HARVESTER

```
Input  : Antenna size constraint, Aimed center frequency
Output: Geometric architecture of optimal antenna, Performance of designed antenna
Objective Function: Φ(W, L, y_0, g) ;
Initialization: x_i^j = x_min^j + randn(0,1) · (x_max^j − x_min^j) ;
while t ≤ Maximum Generation do
    Mutation Operation;
    for i = 1: NP do
        V_{i,G} = X_{r1,G} + F · (X_{r3,G} − X_{r2,G})
    end
    Evaluate the fitness value Φ_i ;
    Cross Over Operation;
    for i = 1: NP do
        j_rand = [rand(0,1) · D];
        for j = 1: D do
            if rand[0,1]≤ CR or j = j_rand then
                U_{i,G}^j = V_{i,G}^j
            else
                U_{i,G}^j = X_{i,G}^j
            end
        end
    end
    if Φ_i ≤ Φ_j then
        Replace j by the new solution
    else
        Locally optimal value remian
    end
    Solutions are selected and the locally optimal value is found ;
end
Search the global optimum design of RMPA antenna ;
End
```

QPSO algorithm for RMPA design

The evolutionary particle swarm optimization (PSO) is a global search technique with incomparable advantages in searching speed and precision. It was originally introduced by Kennedy and Eberhar [34–36]. The basic idea of PSO is inspired by the social behavior of interactions between members including birds and fish. There are three main attractive features of PSO: robust search ability, fast computation and easy implementation [34, 35, 37]. In addition to its advantages, it has a slow solution fine-tuning ability of the solution, which sucks the solution towards the locally optimum value.

Accordingly, QPSO, as the modified PSO technology, was proposed to enhance the global search ability. The essential difference between the QPSO and PSO is that the movement of particles follows the principles of quantum mechanics instead of Newtonian mechanics.

The general governing equation in quantum mechanics of QPSO is the time independent Schrödinger equation:

$$\widehat{H}(r) = -\frac{\hbar^2}{2m}\nabla^2 + V(r) \tag{50}$$

With the Monte Carlo method [34, 38], the position of particles can be updated by:

$$x_d^j(k+1) = p_{j.d} + \beta \cdot \left| Mbest_d^j - x_d^j(k)) \right| \ln(1/u) \tag{51}$$

where the $Mbest_d^j$ can be proposed as the following equation.

$$Mbest_d^j = \sum_{j=1}^{N} \frac{p_d^j}{N} \tag{52}$$

During the whole procedure, the local optimal value would be updated. The overall process is described in Algorithm 3

Algorithm 3: QUANTUM-BEHAVED PARTICLE SWARM OPTIMIZATION FOR OPTIMAL ANTENNA IN RF ENERGY HARVESTER

Input : Antenna size constraint, Aimed center frequency
Output: Geometric architecture of optimal antenna, Performance of designed antenna
Objective Function: $\Phi(W, L, y_0, g)$;
Initialization: $x_i^j = x_{min}^j + randn(0,1) \cdot \left(x_{max}^j - x_{min}^j\right)$;
Search local optimum value ;
while *$t \leq$ Maximum iterations* **do**
  Evaluate the fitness value of every individual Φ_i ;
  Update the locally optimum value and the galobal optimal value ;
  if *The individual with global optimal remains* **then**
    Update affinity and concentration value
  else
    Continue
  end
  Update the position of particle by $x_d^j(k+1) = p_{j.d} + \beta \cdot \left| Mbest_d^j - x_d^j(k)) \right| \ln(1/u)$
  Solutions are selected and the locally optimal value is found ;
end
Search the global optimum design of RMPA antenna ;
End

Table 5 Some assumed properties of designed antenna

Parameter	Value
Height of substrate	1.588mm
Dielectric constant	4.4
Loss tangent	0.008

Results

The GSM1800 frequency band has been considered to test the validity of the proposed algorithms. The objective function has already been mentioned in Eq. (2), and the weight matrix **W** was set to [0.3,0.4,0.3]. Some assumed antenna properties have been shown in Table 5.

Optimal antenna for GSM1800

The GSM1800 band is allocated in the frequency band 1805.2 $\sim$ 1879.8 MHz (Downlink), and the three separate optimization technologies have been utilized under two different antenna size constraints including in antenna size less of than 100 mm as well as an antenna size of less than 150 mm. Additionally, the parameters which are used in the QPSO, CS, and DE algorithms are shown in the Table 6. The proposed algorithms were all implemented in MATLAB and Python, and executed on an Intel core^{TM} i5 duo PC with 3.10 GHz CPU and 8 GB RAM.

Test case 1: antenna size should be less than 100 mm

For the case that antenna size should be less than 100 mm, the comparison of objective function values against a number of iterations for each of the three algorithms is shown in Fig. 6. The proposed algorithms successfully converge on their minimum solutions. Moreover, the graph illustrates that the DE algorithm performs better than the other two approaches in terms of overall convergence performance. The CS algorithm did not give as effective a convergence ability in comparison to the QPSO and DE approaches in the simulation. The results of simulating the proposed optimal antenna designs obtained from the three bio-inspired algorithms are listed in Table 7.

Table 6 Parameters setting of algorithms QPSO, CS, and DE

Algorithms	Parameter	Value
QPSO	α	0.75
	Max iterations	500
	Population size	20
CS	P_a	0.3
	Number of nest	20
	Max generation	500
	β	1
DE	Mutation strategy	DE/rand-to-best/1
	Crossover strategy	binomial crossover
	F	0.5
	CR	0.3
	Numbers of population	20
	Max generation	500

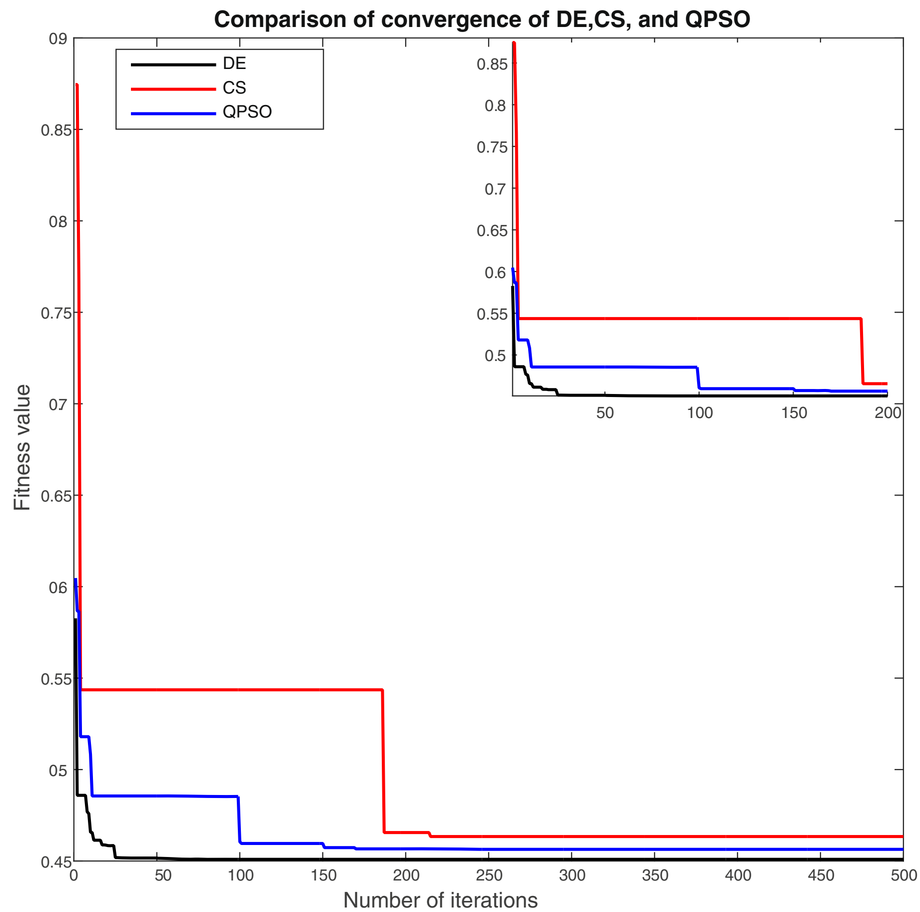

Fig. 6 Comparison of simulation processes of QPSO, CS, and DE with W < 100 mm constraint. This figures shows the comparison of the simulation processes of the three methods with the constraint of W < 100 mm. The partial drawing at the top right corner shows the fitness function before convergence

Test case 2: antenna size should be less than 150mm

Similar results are obtained when the antenna size has to be less than 150 mm. The convergence characteristics of the three optimization methods are shown in Fig. 7, and it indicates that both the DE and QPSO algorithms are effective, each with a high location accuracy and fast convergence speed. The detailed design parameters for the case 2 where antenna size must be less than 150 mm are shown in Table 8.

Table 7 Summary of the properties of designed antenna based on QPSO, CS, and DE for antenna size less than 100 mm

Property	DE	CS	QPSO
Antenna gain (dBi)	3.01	2.812	2.932
Antenna effciency	0.445	0.425	0.435
Efficient bandwidth ratio	0.3463	0.3263	0.3383
Patch width (mm)	99.711	90.529	96.483
Patch length (mm)	37.448	37.664	37.571
Inset feed length (mm)	9.032	27.279	27.354
Notch width (mm)	0.256	0.2574	0.2568
Run time (s)	66.2068	100.621	59.156

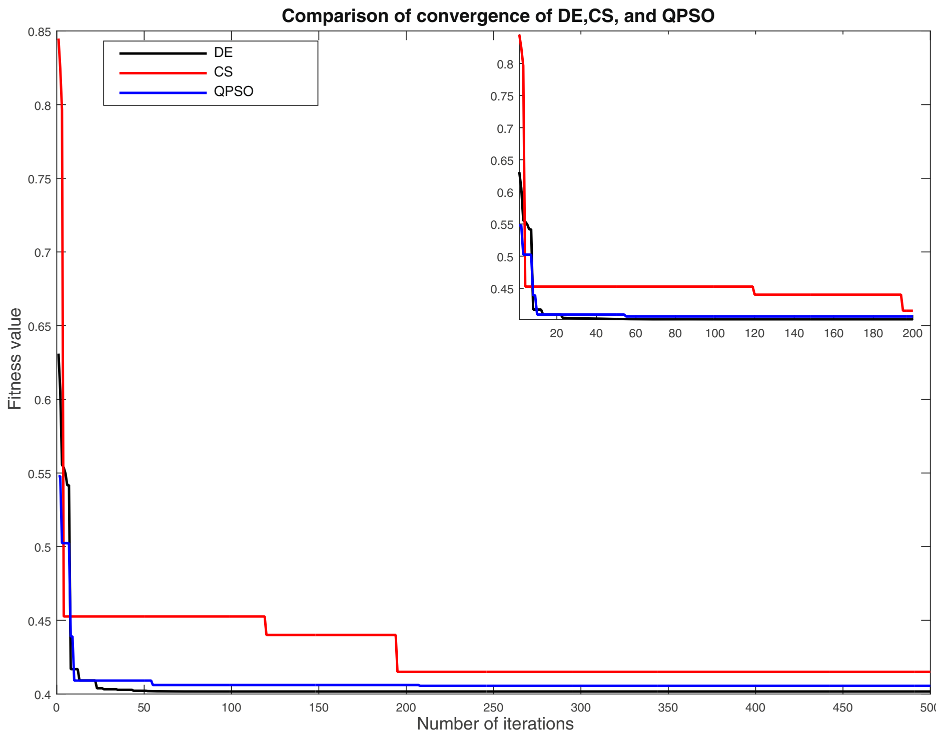

Fig. 7 Comparison of simulation processes of QPSO, CS, and DE with W < 150 mm constraint. This figures shows the comparison of the simulation processes of the three methods with the constraint of W < 150 mm. The partial drawing at the top right corner shows the fitness function before convergence

Discussion

On comparing Figs. 8 and 9, it can be seen that the antennas designed based on each of the three bio-inspired algorithms provide significantly improved properties especially for antenna gain (Fig. 8a) and the bandwidth (Fig. 9a) over non-optimised solutions. Amongst the three optimization approaches, the DE solution offers the widest bandwidth, highest antenna efficiency, and highest antenna gain, identifying that the DE algorithm has an excellent global search ability. In addition, the QPSO based technology presents its incomparable fast and robust convergence ability as shown in Fig. 9b. With the same number of iteration, the speed of convergence of QPSO is 50.44% faster than the CS, and 39.23% faster the DE algorithm. Results in Fig. 8b indicates that the CS algorithm has the best robustness performance. On contrast, DE is sensitive to the parameters used in

Table 8 Comparison between the properties of designed antenna based on QPSO, CS, and DE for antenna size less than 150 mm

Property	DE	CS	QPSO
Antenna gain (dBi)	3.82	3.78	3.736
Antenna effciency	0.4902	0.45	0.483
Efficient bandwidth ratio	0.425	0.4115	0.411
Patch width (mm)	150	147.1	149.04
Patch length (mm)	37.294	37.285	37.75
Inset feed length (mm)	2.2649	29.21	$3.23 \cdot 10^{-5}$
Notch width (mm)	0.2549	0.2549	0.0374
Run time (s)	92.181	99.606	66.2068

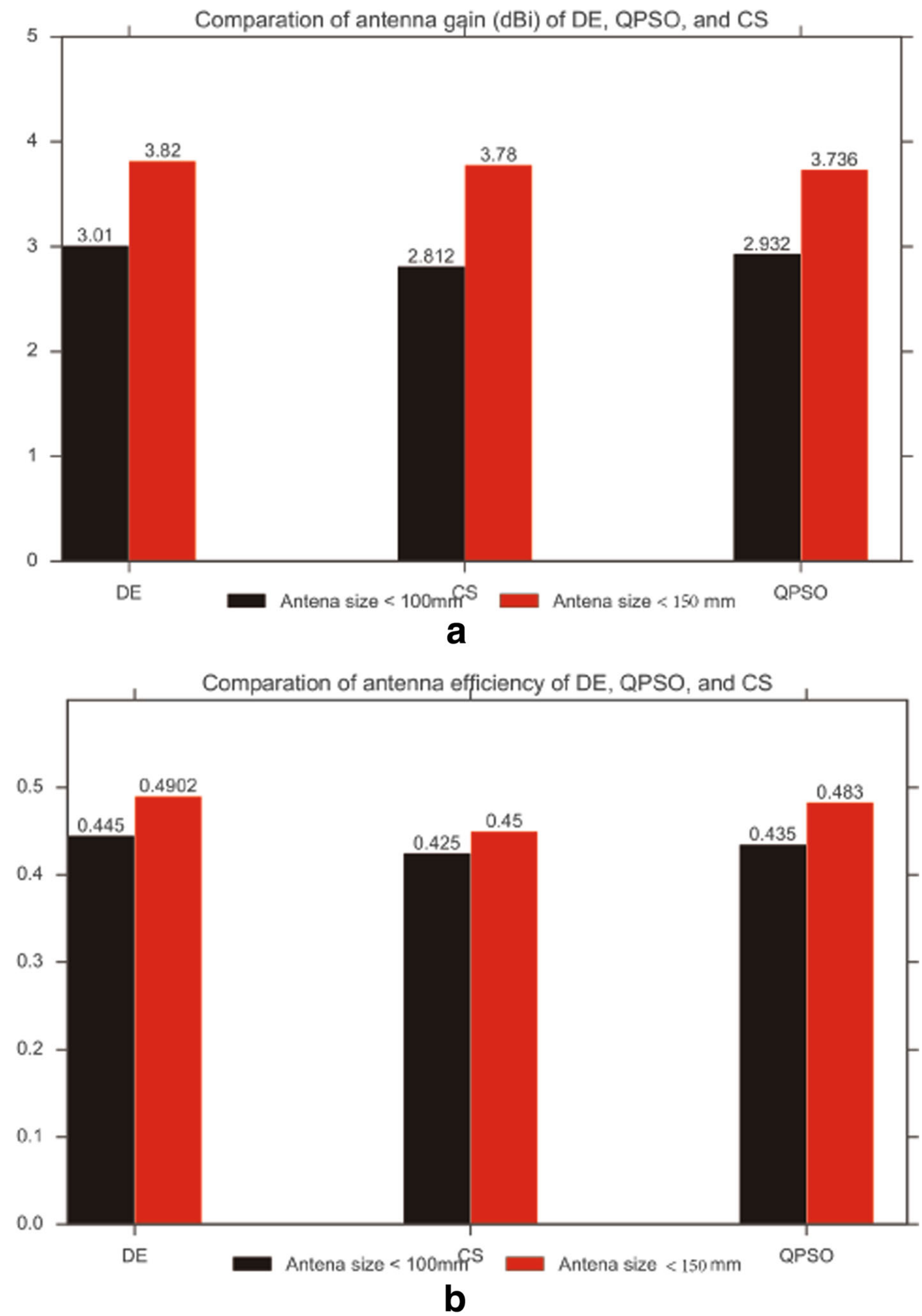

Fig. 8 Comparison of antenna gain and efficiency of DE, QPSO, and CS. These figures show the comparison of antenna gain and efficiency of the antennas designed by the three methods with the constraint of W < 150 mm and W < 100 mm

the simulation. Furthermore, the two tests also show that the increase of antenna size can potentially boost the performance of the antenna. In other words, there is a trade-off between the minimization of antenna size and the antenna performance.

Conclusion

The general anatomy of an RF energy harvester has been explained and examined. Some state of the art designs for receiving antenna including both narrow-band and broad

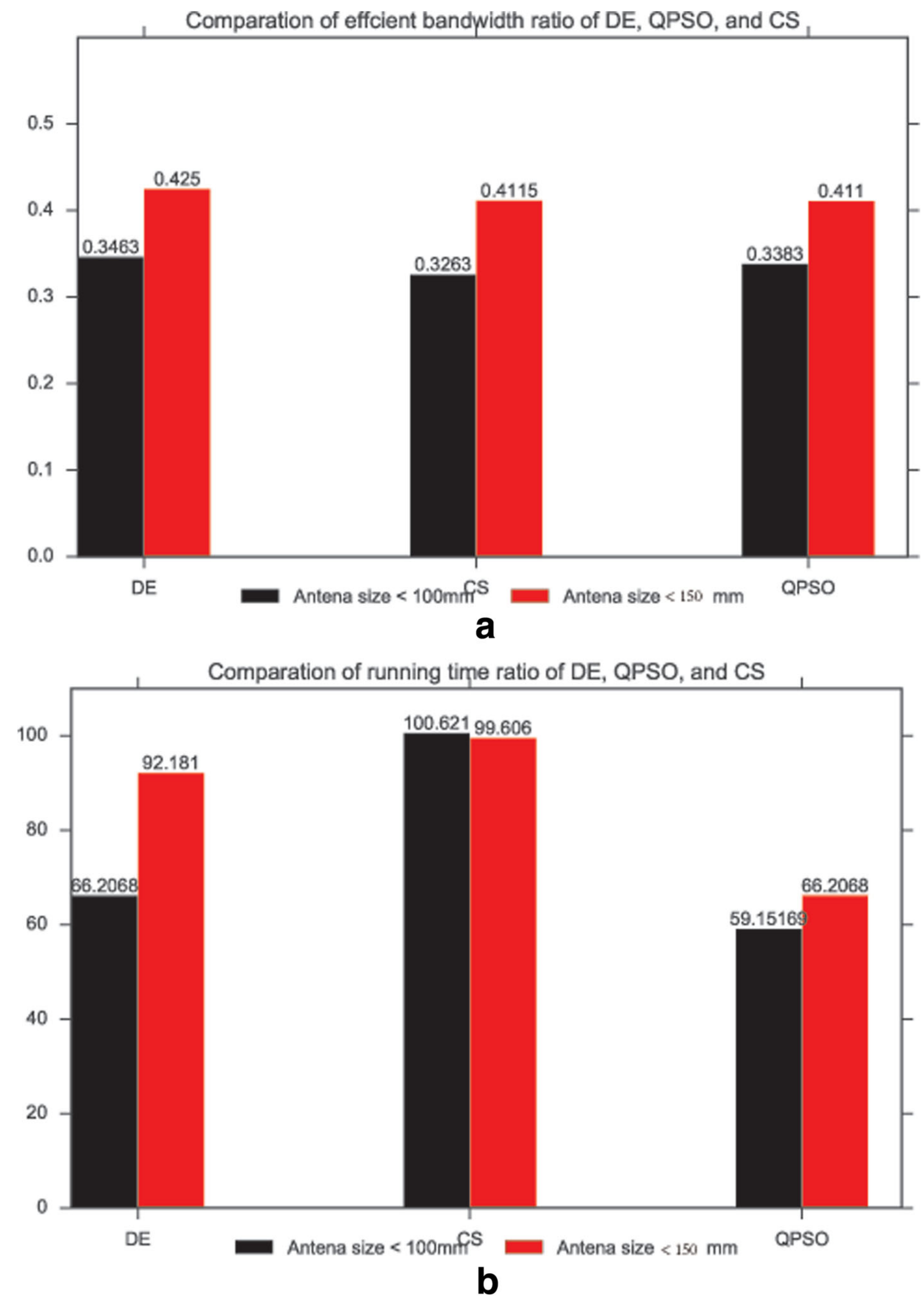

Fig. 9 Comparison of of DE, QPSO, and CSof DE, QPSO, and CS. These figures show the effcient antenna bandwidth ratio and running time designed by the three methods with the constraint of W < 150 mm and W < 100 mm

band antennas have been introduced. In the second part, a mathematical weighted evaluation model involving antenna efficiency, center frequency, bandwidth, and gain was proposed to evaluate the performance of a RMPA for a RF harvesting system.The heuristic optimization approaches CS, DE, and QPSO were introduced and then utilized to give optimal designs for a GSM1800 receiving antenna. The proposed optimization algorithms successfully achieved optimal solutions under two different antenna size constraints. The overall comparison between QPSO, DE, and CS showed that the DE based optimization design approach provides the best solution and hence has the best globally optimum value search ability. This can significantly enhance antenna performance. Moreover, among the three optimization approaches, the CS algorithm has the best robustness. Furthermore, the simulations using QPSO based algorithm indicate its superiority displaying a faster convergence speed than DE and CS in the application of solving a complex electromagnetic problem.

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